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LA-UR-86-2590

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Received by OSTI

AUG 05 1986

CONF-8606182--1

Los Alamos National Laboratory is operated by the University of California for the United States Department of Energy under contract W-7405-ENG-36

LA-UR--86-2590

DE86 013825

TITLE: CYGNUS EXPERIMENT AT LOS ALAMOS

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SUBMITTED TO: The Proceedings of the 5th Course of the International School of Cosmic Ray Astrophysics, "Ettore Majorana" Center for Scientific Culture, Erice, Italy, June 1-9, 1986

Los Alamos

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Los Alamos, New Mexico 87545

FORM NO 836 R4
ST NO 2629 5/81

Cygnus Experiment at Los Alamos

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Abstract

The Cygnus experiment at Los Alamos National Laboratory has been designed to study, with high angular accuracy, point sources of gamma rays of energy above 10^{14} eV. The experimental detector consists of an air shower array to observe gamma-ray showers and a shielded, large-area track detector to study the muon content of the showers. In this paper we present preliminary data from the array and describe its performance.

Introduction

The study of ultra-high-energy cosmic ray gamma rays provides an exciting new window to explore the origin of high-energy cosmic rays (A. M. Hillas 1984). The interest in this field has grown steadily since the first report of observations of point sources (Stepanian et. al., 1972, Ramanmurthy and Weekes 1982, A. A. Watson 1985). The reports of the Kiel group (Samorsky and Stamm 1983) showed strong evidence for a signal from Cygnus X-3, that showed phase correlation with the orbital period as seen in X-rays. This result also suggested that the observed showers had a muon content much higher than would be expected from gamma-ray-induced showers. Since then, other experiments using both air showers techniques and underground muon detectors have reported results of varying statistical significance. If showers from Cygnus X-3 are muon rich relative to expectation they may indicate the existence of new particle physics phenomena either at the source or in the interactions of high-energy gamma rays with atmospheric nuclei (Barnhill et. al., 1985). None of these experiments (Kiel excepted) has shown a significant signal without the use of phase analysis.

The Cygnus experiment at Los Alamos National Laboratory was designed to search for the presence of point sources of ultra-high-energy gamma rays and to study the muon content of their air showers. This detector was designed to have an angular accuracy of better than 1°, in order to improve the signal-to-background ratio of this experiment. Los Alamos was chosen

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as the location of this experiment for several reasons. First, there exists at LAMPF a working, fine-grained track detector (E225), which can be used to detect muons in a clear and unambiguous manner. Second, the detector is located at an altitude of 7000′, which allows this experiment to observe showers produced from lower energy gamma rays than previous air shower experiments done at lower altitudes. Third, the facilities of Los Alamos National Laboratory were available to facilitate the construction and operation of this experiment.

EAS Detector Design

The EAS detector consists of 64 counters placed in an array of radius 60 meters with a typical separation of 14 meters. Each counter contains a scintillator, approximately 1-m^2 by 8-cm thick, with a 2-inch photomultiplier tube positioned 70 cm above the scintillator. Single minimum-ionizing particles selected by small scintillator paddles result in a timing resolution of standard deviation 1.6 ns and produce about 20 photoelectrons in the photomultiplier tube.

EAS Trigger

Every counter is used in making the trigger decision as well as in giving pulse-height and timing information. The basic trigger requires that a given number of counters must fire their individual discriminators within a 300 ns interval, the time for an EAS with a zenith angle of 45° to the array. The discriminators responsible for the trigger are also used to determine the timing, so the threshold is set very low, about 1/10 of a minimum ionizing particle, in order to fire the discriminator on the earliest photoelectron.

A software cut is implemented to eliminate non-analyzable showers before they are recorded on magnetic tape, which reduces our data-taking rate by about a factor of five. Figure 1 shows the online display of a typical event that passes the software criteria.

Muon Detector

Muon information is also recorded for every trigger. The muon detector was designed for studying the elastic scattering of accelerator-produced neutrinos with electrons (E225) and is currently being used for that purpose (Allen, 1985). A multiplexing circuit allows both the neutrino and the air shower experiment to use the detector simultaneously. The detector is shielded above by 1700 g/cm^2 of steel and concrete. Two components of the detector - the multiwire proportional chambers (MWPCs) and the flash chamber calorimeter - are used to determine the muon content and direction in showers. The MWPCs surround the detector with four layers on all six walls except the floor, which has only one layer. Each MWPC is typically 520-cm long by 20-cm wide by 5-cm thick and the horizontal area is 36 m^2. The muon number can be determined exactly for small numbers and systematically for higher densities.

The 208,000 flash chambers cover a volume of 350 by 305 by 348 cm^2 and have sufficient resolution to determine the muon direction and number, as can be seen from the example of Fig. 2. Simulations of a fitting algorithm show that 95% of the tracks can be reconstructed to within 0.5°. However, the flash chambers cannot be triggered for all EASs, which come at a rate of 1.2 Hz.

Smart Trigger

The rate at which it is reasonable to fire the flash chambers in the E225 calorimeter is 0.02 Hz. It was necessary therefore to reduce the rate of triggers to the E225 detector by a factor greater than 50. A computer-controlled hardware trigger was devised to allow only events that come from a specified direction to trigger E225. This smart trigger was needed because the flash chambers must be fired within a microsecond of particles traversing it. This does not allow for timing information to be digitized or processed. The direction of a suspected source moves 1° in four minutes; hence the trigger must be continually updated. This is accomplished by the use of ECLine Camac programmable logic delays. The gates for this trigger are set to a width of 8 ns and the relative delays of each counter are set to zero for showers coming from the source direction. A multiplicity coincidence level is set and only showers coming near the desired direction are accepted. In Fig. 3, we show a plot of the sky (right ascension and declination). The crosses are showers that pass the smart trigger criteria over a 24-hour period in which three sources were being watched, Cygnus X-3, the Crab, and Herc X-1. This trigger selects events in a cone of half angle 9° and gives a trigger every 2 minutes when a source is overhead.

Monte Carlo Calculations

Monte Carlo calculations were performed to study the design and triggering conditions of the array. These calculations included proton- and gamma-ray-induced showers. The primary energies were selected from a spectrum and the cores of these showers were thrown over the area of the detector and the surrounding areas. The hadron component of these showers was simulated fully. Electromagnetic showers were followed down to 500 GeV where Approximation B was used for longitudinal development. The radial distribution of each sub-shower was computed. Muon densities were computed for annular rings for each shower. Differing trigger conditions where imposed and rates for each were computed.

The results of the simulations show that with a trigger requirement of 10 counters, each having more than 2 equivalent minimum ionizing particles, the effective threshold for proton showers is 10^{14}eV, while gamma-ray-induced showers have a threshold of 2 x 10^{14}eV. The muon simulation showed that the E225 detector contained at least one muon for 80% of proton-induced triggers. This number is consistent with the observed number of 75% of showers having one or more muons in data.

The Monte Carlo calculation was also used to study reconstruction algorithms. These simulations showed that with a timing resolution of 2 ns (for large signals) it was possible to obtain a resolution of better than $0.65°^2$ for showers that passed our threshold.

Reconstruction and Resolution of Events

The event direction is computed by fitting the shower arrival time distribution. The shower front has a curvature, observed to be (~10ns/60m); this is included in the fits. Counters are weighted in this fit so that counters with larger signals are given more significance. An estimate of the resolution of these counters can be obtained by studying the distribution of the quantity $\chi^2\sigma^2/\nu$, where ν is the number of degrees of freedom, $\chi^2\sigma^2/\nu$ should have the average value of σ^2. For our showers this yields a value of $\sigma = 2$ns for greater than three particles signal.

A test of the random reconstruction error in the array can be obtained from data by the following procedure: counters are divided into two groups - odd and even numbered counters. Each group of counters is used independently to reconstruct the arrival direction. The space angle between these directions is found to have a median value of $< 1°$. This predicts a resolution for the combined array of $< 0.75°^2$. Work is still being done to improve this resolution.

Three independent tests of pointing accuracy are being undertaken. First, the arrival direction of muons detected in the E225 flash chambers is being compared to the air shower data. Preliminary results indicate reasonable agreement between the two directions, consistent with the expected multiple scattering angle of the muons in the shielding.

Second, a small Cherenkov array has been deployed at the experiment site. This array will be used to determine shower direction and energy in a way that is systematically different from the air-shower method. Tests have been made with these counters and some data have been taken.

Third, we plan to use our existing data to study the shadow of the moon using ordinary hadron data. If our accuracy is greater than $(1°^2)$, then we should see a substantial reduction of data in bins which contain the moon position. This technique may also work with the sun.

Status

The experiment has been in operation since early March 1986 with more than 40 scintillation counters and with the MWPC information. More than 10^6 events have been recorded. As of July 15, 54 counters are deployed, and by the end of the year nearly 100 detectors will compose an expanded array of radius 90 m. The flash chamber multiplexing scheme is operational, and data are being recorded on a regular basis.

An additional detector (E645) that can give information on muon number and direction, is coming on line this summer to study the oscillations of accelerator-produced neutrinos (Smith, 1985). This detector, consisting of liquid scintillator and drift tubes, has a horizontal area of 56 m^2 and an overburden of 3000 g/cm^2. Liquid scintillator information has been successfully recorded for EAS triggers.

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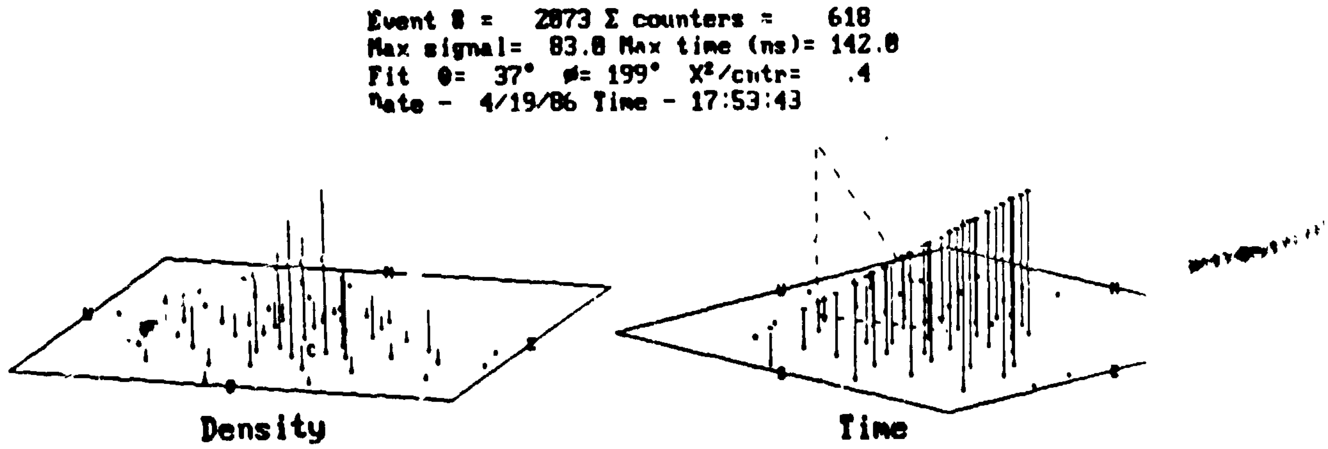
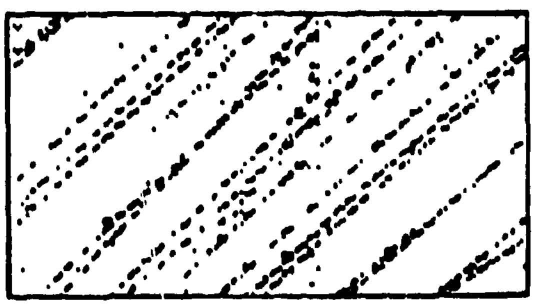


Fig 1. Density profile and arrival time of an EAS event.



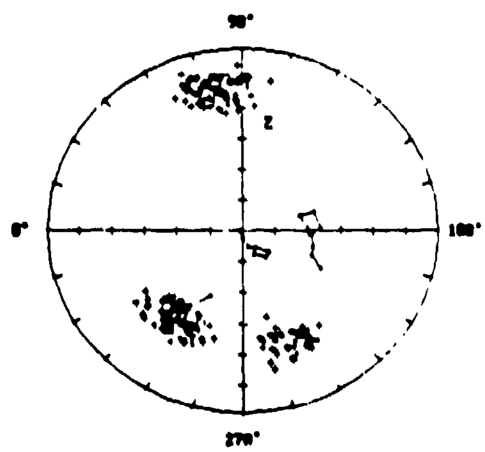


Fig 2. Side view of flash chambers. Fig 3. RA and Dec for smart trigger.